

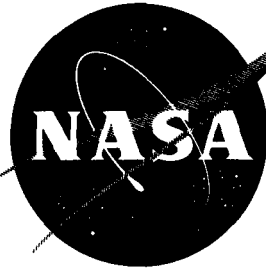
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TECHNICAL MEMORANDUM

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CASCADE INVESTIGATION OF COOLING CHARACTERISTICS OF A
CORRUGATED-INSERT AIR-COOLED TURBINE BLADE FOR
USE IN A TURBOPROP ENGINE

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CASCADE INVESTIGATION OF COOLING CHARACTERISTICS OF A CORRUGATED-INSERT
AIR-COOLED TURBINE BLADE FOR USE IN A TURBOPROP ENGINE*

By Hadley T. Richards

SUMMARY

The cooling effectiveness of a small air-cooled turbine blade for use in a turboprop engine was experimentally investigated in a static cascade facility. Three test blades of 1.4-inch span and 0.7-inch chord were subjected to combustion-gas temperatures of about 1060°, 1360°, and 1660° R. The blade cooling-air temperatures ranged from about 560° to 800° R. Gas Reynolds numbers varied from 85,000 to 380,000.

The cooling effectiveness of the corrugated-insert blade reported herein was found to be almost identical with that of a cast-finned blade investigated previously. At the root region, the corrugated-insert blade was from 18° to 65° F cooler than the cast-finned blade. This range of temperatures corresponded to about a 10-percent improvement in the cooling effectiveness of the blade.

A nondimensional method of correlating the experimental heat-transfer data of the blades, which had been developed for a preceding blade design (previously reported), was utilized successfully with the data of this investigation.

INTRODUCTION

The benefits obtained by increasing the turbine-inlet temperature of turboprop engines and the thermodynamic effects on engine performance of cooling the turbines are reported in reference 1. The problems of cooling blades for possible application in the turbines of turboprop engines are discussed in reference 2. A further discussion of the problems of cooling small blades can be found in reference 3. As part of a program for investigating cooled turbine blades for turboprop engines, a blade with an outer profile the same as that reported in reference 2, but of different construction and internal heat-transfer surface configuration, has been investigated at the NASA Lewis Research Center. The

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blade configuration investigated was of the corrugated-insert type. It was expected that the increased internal heat-transfer surface area, relative to that of the design reported in reference 2, would promote more efficient cooling. The blade had a span of 1.4 inches and a chord of 0.7 inch. The entire airfoil portion of the blade was made from sheet-metal components brazed into a cast-metal base.

The purpose of the present investigation was twofold. One objective was to determine the cooling characteristics of the corrugated-insert-type turbine blade and to compare its cooling performance with that of the cast-finned blade previously reported in reference 2. A second purpose was to provide further corroboration of the correlation procedure originally evolved in reference 2.

The cooling characteristics of the corrugated-insert blade were determined in a static cascade test facility that accommodated nine blades. Three blades in the central part of the cascade were instrumented with thermocouples. The blades were investigated at combustion-gas temperatures of about 1060°, 1360°, and 1660° R. Use of an existing facility (used in ref. 2) for the supply of combustion gas limited the maximum temperatures to 1660° R, but still allowed further check of the correlation presented in reference 2. The gas Reynolds number ranged from about 85,000 to 380,000. Blade cooling-air temperatures ranged from 560° to 800° R, and the cooling-air Reynolds number from about 2100 to 20,000.

SYMBOLS

$d_{h,a}$ coolant passage hydraulic diameter ($4 \times$ flow area)/wetted perimeter, ft

$d_{h,g}$ gas-side hydraulic diameter (average blade gas-side perimeter)/ π , ft

f function

g acceleration due to gravity, ft/sec²

Re Reynolds number, $\rho V d_h / \mu_g$

T temperature, °R

V velocity, ft/sec

$$z_T = \frac{(\overline{Re}_{g,b})^{0.7}}{(\overline{Re}_{a,i})^{0.8}} \left(\frac{\overline{T}_b}{\overline{T}_{a,i}} \right)^{1.25}$$

- μ viscosity, (lb)(sec)/sq ft
- ρ density, lb/cu ft
- Φ temperature-difference ratio, $(T_{g,e} - T_b)/(T_{g,e} - T_{a,i})$

Subscripts:

- a cooling air
- b blade
- e effective
- g combustion gas or combustion-gas side
- i inlet
- T turbulent flow

Superscripts:

- average conditions at particular span location
- = average conditions for entire blade

APPARATUS

Blades

The turboprop turbine blade used in this investigation had a span of 1.4 inches and a chord of 0.7 inch, the same as that used in the first blade design (ref. 2). Analysis of several internal designs indicated that one with thin sheet-metal corrugations might have some advantage from the standpoint of heat transfer over the semistrut design used in reference 2. A blade that utilized sheet-metal components of 0.005- and 0.010-inch thickness, furnace-brazed together, was built, as shown in figure 1. Cross-sectional views of the blade at three span-wise locations are shown in figure 2.

The outer shell, both pressure and suction surfaces, was separately formed of Haynes Alloy 25 by a stretch-forming process. The thickness of the material was constant at 0.010 inch. The same material of 0.005-inch thickness was formed into corrugations with an amplitude of 0.025 and a pitch of 0.050 inch. In an initial brazing operation, these corrugations were brazed to the inner side of the pressure-surface and suction-surface blade shells, as shown in figures 1(a) and (c). The

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brazing was done in an induction-heated, vacuum-atmosphere furnace with the use of a commercial brazing material. It should be noticed that only on the suction surface do the corrugations extend from the base to the tip of the blade shell (fig. 1(a)). At 50 percent of the span, the pressure-side corrugations are terminated because of the lack of space within the blade cavity (fig. 1(c)). The smaller sheets of metal on the inner surface of the suction and pressure shells shown in the photograph form an inner island at blade assembly. This island is necessary to force cooling air to follow the passages formed by the corrugations near the outer surface of the shell.

The base of the blade was cast of X-40 alloy and was joined to the shell in a second brazing operation that also joined the two halves of the shell. The base was then ground to the shape necessary to accommodate the blade in the cascade test section. The completed blade is shown in figure 1(d).

Test Facility

The cascade test facility was the same as that described in detail in reference 2 except for the method of mounting the three test blades in the central region of the cascade. In order to overcome the cooling-air leakage that was encountered in the apparatus of reference 2 and thus eliminate the necessity of leakage calibration tests, the coolant supply to each of the three test blades investigated herein was provided by employing separate coolant supply tubes. These tubes were welded directly to the bases of the individual test blades and were connected to a cooling-air plenum, as shown in figure 3. The supply tube from this chamber was attached to the pipe from the cooling-air regulating and metering equipment. Air from a 125-pound-per-square-inch source was filtered through a 25-micron filter and was reduced in pressure to the metering rotameters.

INSTRUMENTATION

Blades

Eighteen thermocouples, six in each blade, were installed in the three test blades at the locations shown in figure 2. The spanwise locations correspond approximately to the root, midspan, and tip. The blades were instrumented by cementing thermocouples made of 36-gage (0.005-in. diam.) Chromel-Alumel wire in shallow grooves (approximately 0.008 in. deep) in the surface of the blade. The output electromotive force of these thermocouples was read on a potentiometer calibrated in degrees Fahrenheit.

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Cascade

The instrumentation of the cascade was unchanged from that described in reference 2 with the exception of the instrumentation within the cooling-air supply chamber. The temperature and pressure of the blade-inlet cooling air were measured by probes inserted within the tank to a depth of approximately 1/2 inch, opposite the entrance of the three tubes supplying air to the cooled blades.

EXPERIMENTAL PROCEDURE

The cooling characteristics of the blades were obtained by measuring the temperatures of the blades over a range of cooling airflows, gas densities, and gas temperatures. The gas conditions were set, and blade temperatures were measured at intervals of varying cooling airflow from zero to choked flow in the blade passages, with suitable time allowed for temperature stabilization at each point. The blade temperatures measured with zero cooling airflow were used as the effective gas temperature $T_{g,e}$ in each series. The gas-flow conditions were changed, and the procedure was repeated. The gas flows per unit flow area ahead of the three test blades ranged from 30 to 52 pounds per second per square foot. This range of flows corrected to sea-level conditions varied from 34 to 36 pounds per second per square foot. The ratio of cooling-air to combustion-gas flow ranged from 0 to about 0.025. The tests were conducted at three gas-temperature levels: 1060°, 1360°, and 1660° R.

CALCULATION PROCEDURE

As in reference 2, the data of this investigation are not presented on an absolute basis, but rather are correlated with dimensionless parameters to permit more general use. The range of coolant Reynolds number at the blade inlet varied from 2100 to 20,000 with the majority of the data in or near the turbulent-flow regime. The correlation equation for turbulent flow derived in reference 2,

$$\bar{\phi} = f(z_T) = f \left[\frac{(\overline{Re}_{g,b})^{0.7}}{(\overline{Re}_{a,i})^{0.8}} \left(\frac{\overline{T}_b}{\overline{T}_{a,i}} \right)^{1.25} \right]$$

was used to correlate the data of this report.

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RESULTS AND DISCUSSION

Before heat-transfer investigation of the blades was begun, surveys of the gas-flow conditions (dynamic pressure and airstream direction) upstream of the test blades were conducted. These surveys indicated no change from the satisfactory flow conditions obtained during the investigation conducted in reference 2.

The correlated data for the corrugated-insert blade are shown in figure 4 for the root, midspan, and tip regions of the blade. The data points represent a correlation of the average blade metal temperatures at each spanwise location for a range of gas temperatures and cooling-air flows. The maximum deviations for a value of $\bar{\phi}$ with respect to the mean lines (solid lines) drawn through the data points were ± 4 , ± 11.5 , and ± 13 percent for the root, midspan, and tip positions, respectively. This deviation of $\bar{\phi}$ from the mean line corresponds to a maximum deviation in blade temperatures (at the blade tip) of $\pm 24^\circ \text{R}$ for an average turbine-inlet gas temperature of 1660°R and a cooling-air temperature of 560°R .

Also shown in figure 4 is a series of dash-dot lines that represent the correlation data for the average blade metal temperatures at the root, midspan, and tip of the cast-finned blades investigated in reference 2. In order to directly compare these data with those of the present corrugated insert blade, recalculation of the z_T values of the former blade was necessary. Since the cooling-air inlet area and hydraulic diameter were not the same for the two designs, the cooling-air Reynolds numbers could not be directly compared. Therefore, the Reynolds numbers for the cast-finned blade were recalculated with the dimensions of the corrugated-insert blade so that values of ϕ could be directly compared. Comparison of the correlation curves for the corrugated-insert blade with those of the cast-finned blade show no difference at the tip and midspan locations. In the root region, however, the $\bar{\phi}$ values for the corrugated-insert blade were significantly higher (indicating lower average metal temperatures) than for the cast-finned blade over most of the range of z_T . For a $\bar{T}_{g,i}$ of 1660°R , $T_{a,i}$ of 560°R , and a value of z_T equal to 3.0, the average root region temperature of the corrugated-insert blade would be about 948°R , while the cast-finned blade would be about 1018°R . Thus, for these conditions the corrugated-insert blade would be about 70° cooler at the blade base than the cast-finned blade. For a z_T value of 9.0, and $\bar{T}_{g,i}$ and $T_{a,i}$ of 1660° and 560°R , respectively, the corrugated-insert blade would be only about 15° cooler than the cast-finned blade. The better cooling performance of the corrugated-insert blade, as compared with that of the cast-finned blade in the root region, probably results from the additional internal heat-transfer surface area over the cast-finned design. Also, the thinner suction-surface wall of the corrugated-insert blade, when compared with the cast-finned blade, would contribute to a lower metal temperature for a given set of gas and cooling-air conditions.

Since, in figure 4, the data of each individual spanwise location correlated, a single curve of overall average $\bar{\phi}$ against z_T could be calculated to permit application of the experimental cascade data to engine conditions, as in reference 2.

Because the average blade temperatures at a specific spanwise location correlated very well, as discussed previously, an attempt was also made to determine whether local blade metal temperatures would correlate in the same manner as in reference 2.

As indicated in reference 2, correlation of local value of ϕ over a range of gas temperatures was obtained when the parameter z_T was constant. Examination of figure 4 discloses insufficient data points at any given value of z_T to permit the correlation. One reason for the lack of data at a constant value of z_T over a range of temperatures was the impracticability of controlling all the variables in the parameter. If the use of the data over a small range of z_T (from 5.25 to 5.75) is permitted, local ϕ data for three gas temperatures are available, and an attempt at correlating local ϕ data can be made.

Figure 5 shows the value of ϕ based on local blade metal temperatures plotted against distance from the leading edge of the blade for the pressure and suction surfaces over the range of parameter z_T given previously. Because the blade metal temperatures correlated very well on both an average and local basis, the data curves shown in figures 4 and 5 can be used to estimate the cooling performance of the blades at operating conditions other than those employed in these experiments. The details of the method for so doing are presented in reference 2 and are not repeated here. Reference 2 shows a specific example of the use of the data to estimate the coolant-flow requirements and local blade metal temperature for an air-cooled turboprop engine operating at a turbine-inlet temperature of 2460°R , flight speed of 300 knots, and an altitude of 30,000 feet. Because the cooling performance of the corrugated-insert blade is so similar to that of the cast-finned blade in reference 2, the airflow requirements and temperature distributions reported in the reference would also be applicable to the corrugated-insert design. Actually, the corrugated-insert blade would require slightly less cooling air, would cool better on the suction-surface part of the blade, and would cool somewhat better in the root region of the blade. In an engine application, factors such as fabrication procedures and techniques required in making the blades, rather than the cooling performance, would probably dictate which of the two blade cooling configurations would be more desirable.

CONCLUDING REMARKS

The cooled turboprop blade designs (the corrugated-insert design reported here and the internally-finned design previously reported) are the result of analytical investigation of a number of possible designs. Selection was based on attaining reasonably high cooling performance with designs that appear to have potential from a fabrication standpoint. All of the blades reported here and in reference 2 were made at the Lewis Research Center and are essentially "handmade" products. It is believed that the cooling performance of the corrugated-insert blade and the cast-finned blade are about as high as can be attained in forced-convection air-cooled turbine blades as small as those considered here and in reference 2. Additional discussion of the effect of blade size on the cooling performance of small blades can be found in reference 3.

SUMMARY OF RESULTS

The results of an investigation in a static cascade to determine the cooling effectiveness of a small air-cooled, corrugated-insert turbine blade suitable for use in a turboprop engine are as follows:

1. The cooling effectiveness of the corrugated-insert blade was found to be almost identical with that of a cast-finned blade previously reported. At the critical midspan section there was no practical difference, while in the root region the additional metal fin area of the corrugated-insert blade and a thinner blade wall section resulted in better cooling (about 18° to 65° R) than with the cast-finned blade.

2. A nondimensional method of correlating the experimental heat-transfer data of the blades, which had been developed for a preceding blade design (previously reported), was utilized successfully for the data of this investigation.

Lewis Research Center

National Aeronautics and Space Administration

Cleveland, Ohio, September 4, 1959

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2. Stepka, Francis S., Richards, Hadley T., and Hickel, Robert O.: Cascade Investigation of Cooling Characteristics of a Cast-Finned Air-Cooled Turbine Blade for Use in a Turboprop Engine. NACA RM E57D19, 1957.

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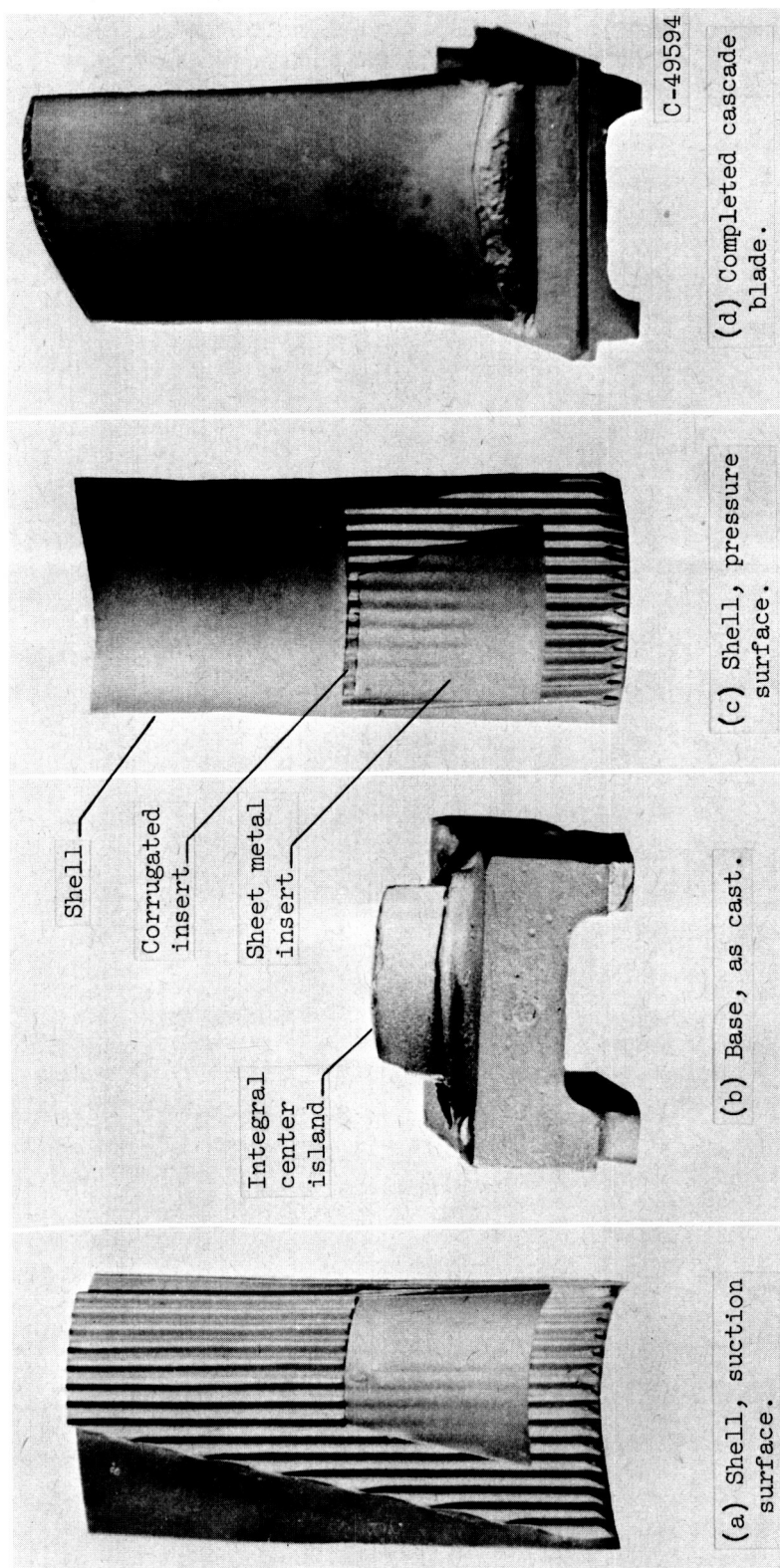


Figure 1. - Corrugated-insert turboprop cascade test blade, parts and completed blade.

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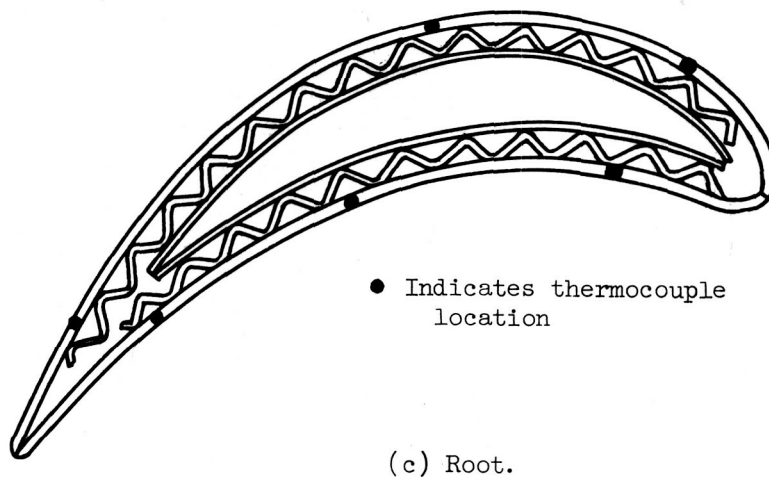
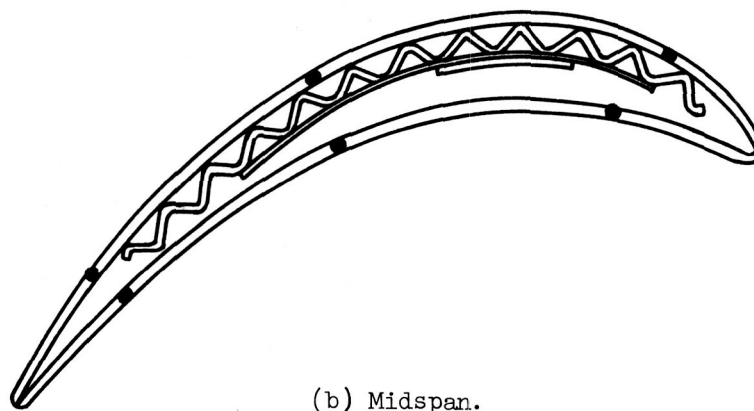
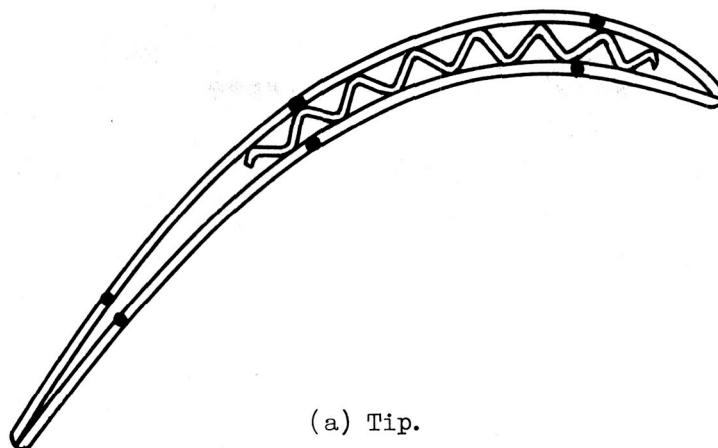


Figure 2. - Cross-sectional view of air-cooled corrugated-insert turbine blade for turboprop engine, showing location of thermocouples.

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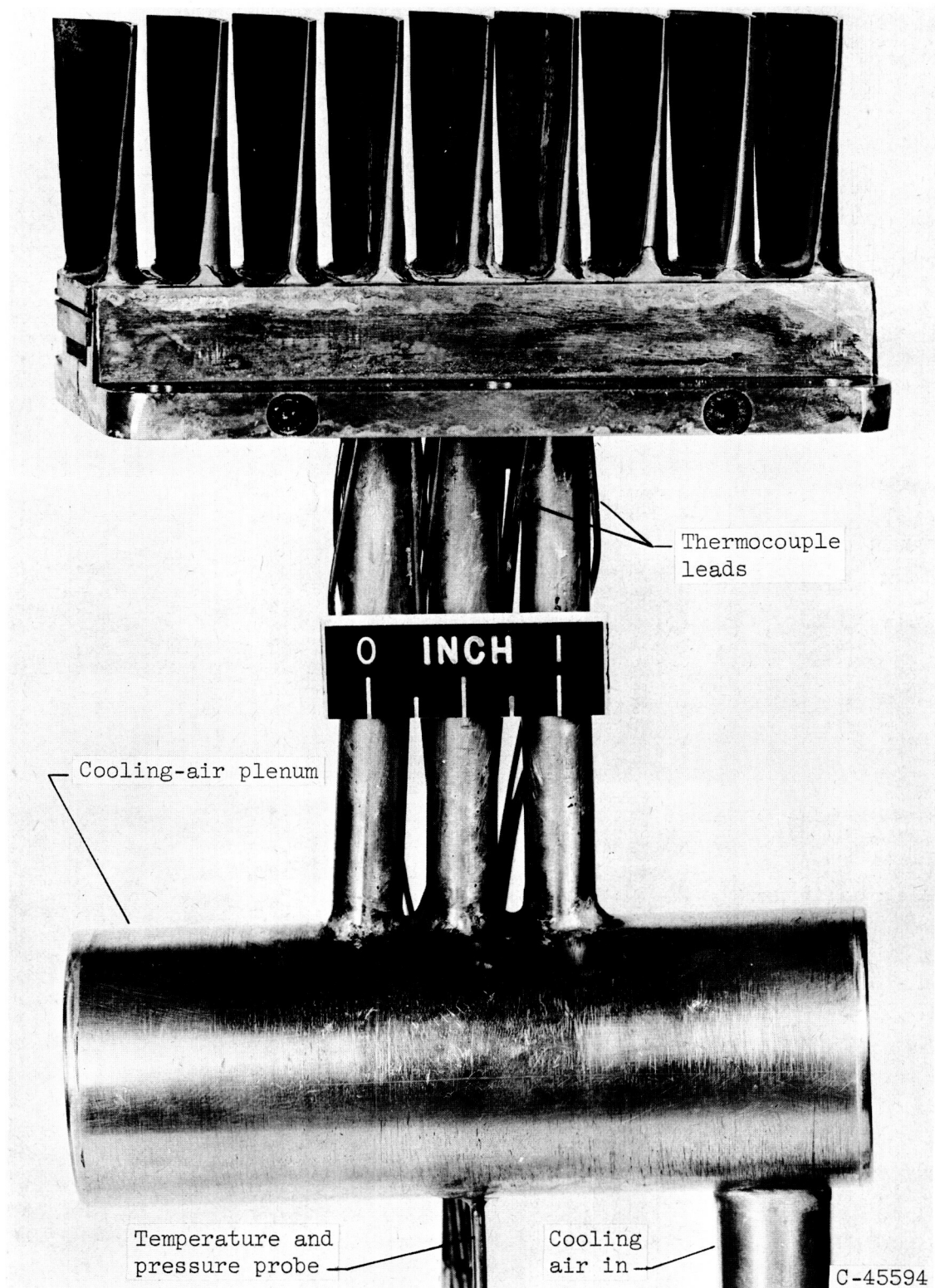


Figure 3. - Corrugated-insert turboprop blades showing cooling-air supply system to the three instrumented blades.

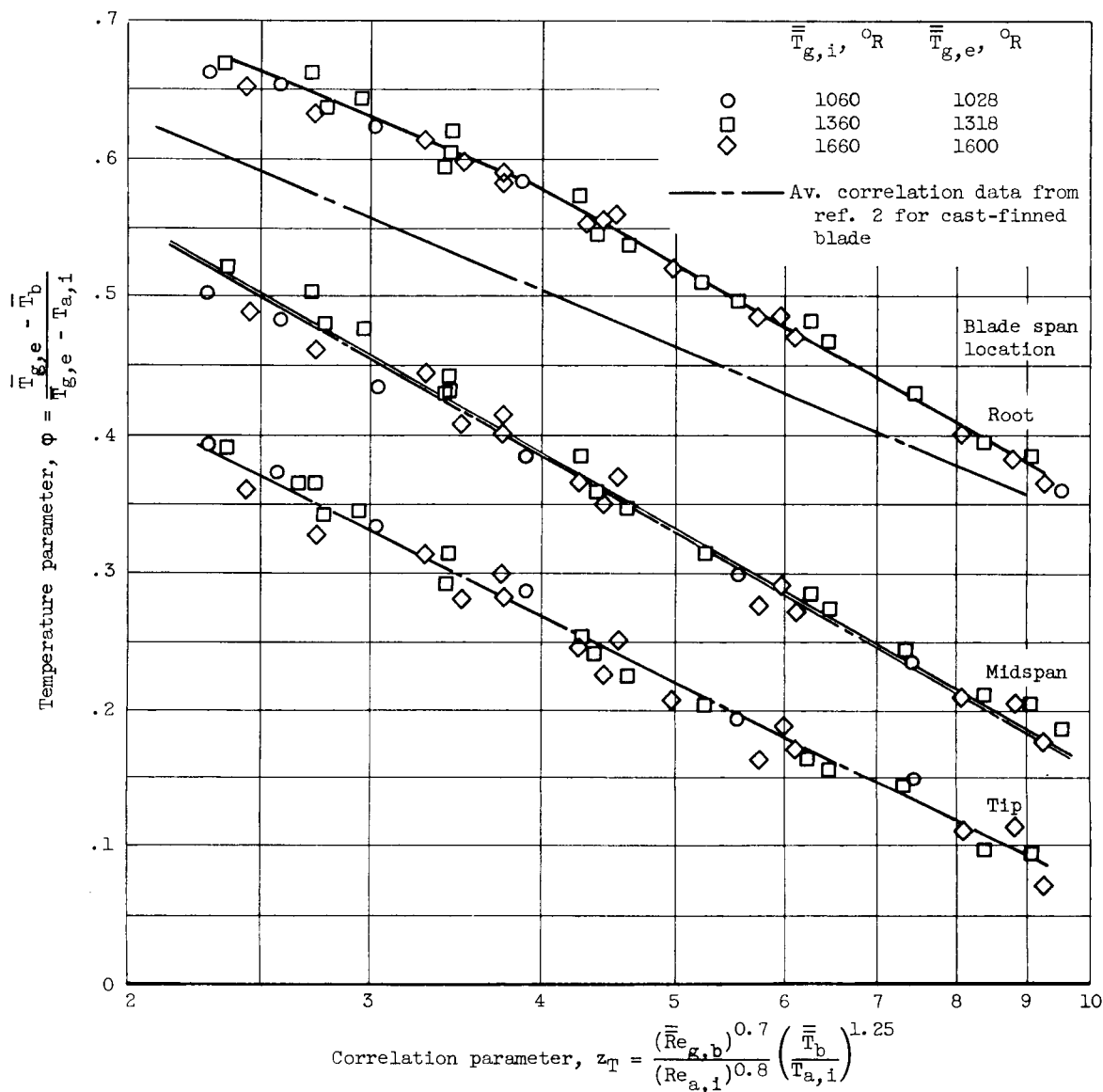


Figure 4. - Correlation of corrugated-insert blade metal temperatures at particular span locations. $T_{a,i}$, 560° to $798^\circ R$; $\bar{Re}_{g,b}$, 0.85 to 3.8×10^5 ; $Re_{a,i}$, 0.21 to 1.99×10^4 .

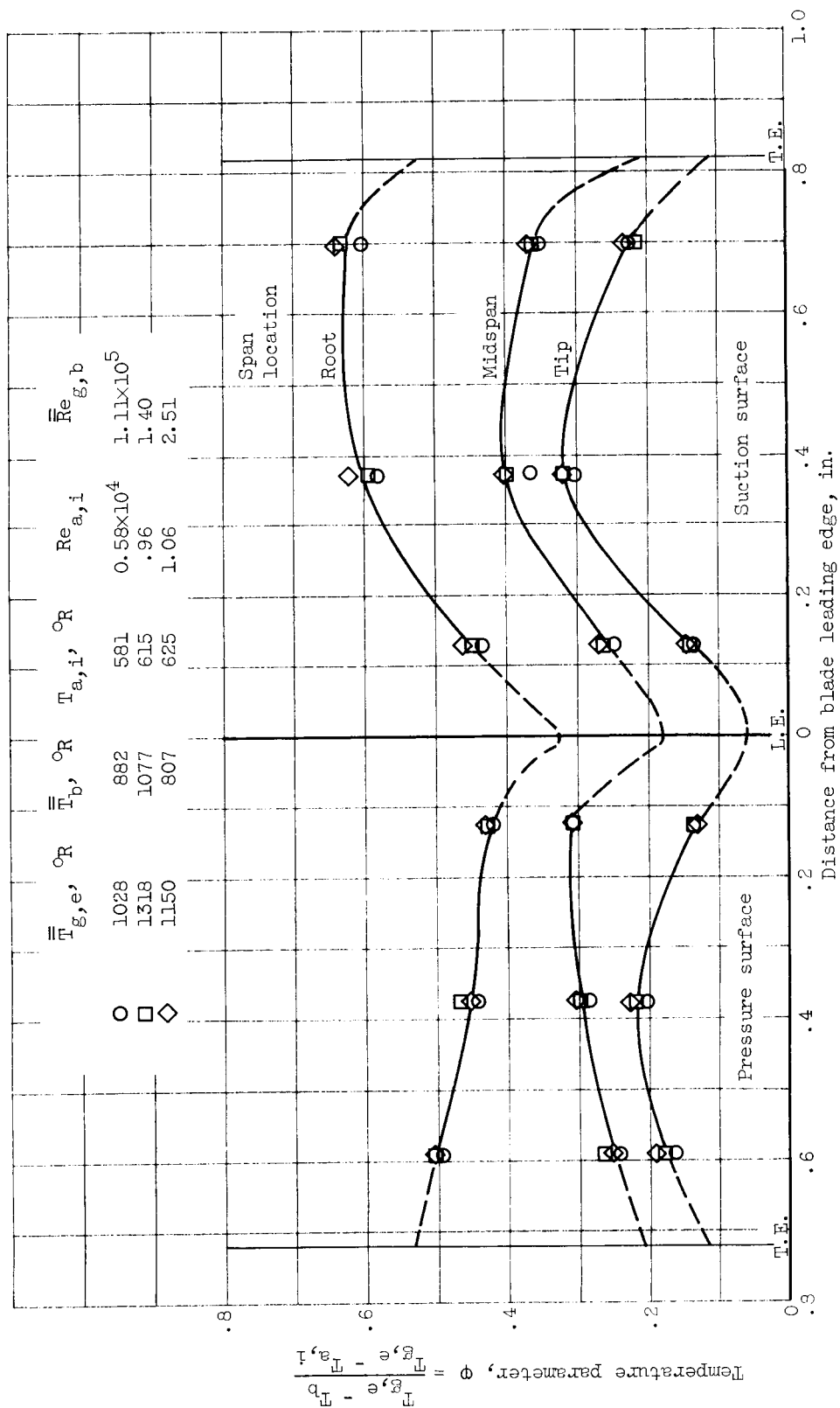


Figure 5. - Typical chordwise variations of local temperature parameter at three spanwise locations.
(Data plotted for z_T value of approx. 5.25.)